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MODELING AND MEASURING EFFECTIVENESS OF C^3 SYSTEMS*

by

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ABSTRACT

A methodology for modeling and evaluating measures of effectiveness of C^3 systems is described. The approach combines the framework provided by the Modular Command and Control Evaluation Structure (MCES) and the quantitative methods of the System Effectiveness Analysis approach. The application to a C^3 problem in which a test bed is used is outlined. Finally, the question of credibility is addressed, when only data from test beds and demonstrations are available for evaluating measures of effectiveness.

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1. INTRODUCTION

Improvements in weapon system technology, and higher capacity and speed in data transmission, combined with an increasing complexity of the battlefield, impose severe time constraints on hardware, software, and human decisionmakers. The purpose of this paper is to present a methodology that is being developed at MIT for modeling and computing measures of performance (MOPs) and measures of effectiveness (MOEs) for C^3 systems. The methodological framework was first applied to C^3 systems by Bouthonnier and Levis [1] and then extended in a series of theses and papers: Cothier and Levis [2], Karam [3], Karam and Levis [4], Bohner [5], and Martin [6].

In the last several years, a series of workshops have been held at the Naval Postgraduate School in an effort to develop generic tools for evaluating C^3 systems and architectures [7]. The Modular Command and Control Evaluation Structure, or MCES, provides a framework for evaluating C^3 architectures in which many different paradigms, models, and algorithmic procedures can be embedded. In this paper, an effort is made to show how the MCES framework and the quantitative System Effectiveness Analysis approach can be integrated to provide a useful way for defining and evaluating MOEs for C^3 systems.

This integration has become possible because both approaches are based on the same six concepts: system, environment, context, parameters, measures of performance, and measures of effectiveness. The first three are used to pose the problem, while the last three define the key quantities in the analytical formulation of the problem. The analytical aspects of the methodology mainly address how hardware characteristics, system structure, and standard operating procedures related to system performance.

The system consists of components, their interconnections, and a set of operating procedures. A boundary can be drawn that defines what is included within the system whose effectiveness is to be assessed; what is included depends on the analysis at hand. The environment consists of our own forces and the adversary's forces, upon which our forces can act and which can act upon ours. For example, a C^3 system is used to monitor (sense) the environment and to direct forces. Engagements between two forces in an urban area or at a mountain pass define typical environments. The context denotes the set of conditions and assumptions within which the system and the environment exist. The relationship between system, environment, and context is shown in Figure 1.

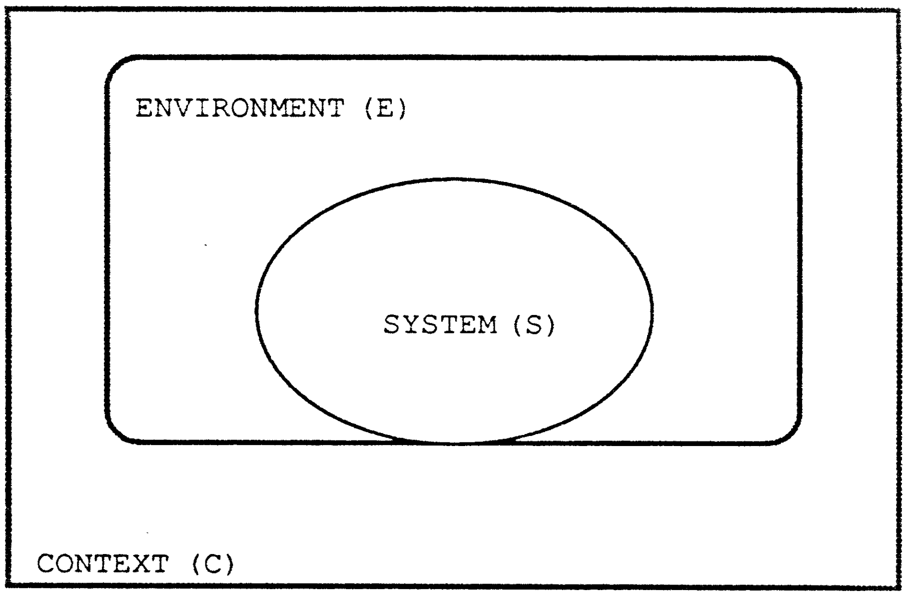

Figure 1. System, Environment, and Context

Parameters are the independent quantities used to specify the system and the mission requirements. For example, in the case of a fire support system, system parameters may include quantities that describe the detection equipment, computational time delays, kill radius of the munition, and failure probabilities associated with the components, to name but a few. Parameters of the mission may be the tempo of operations, as described by the speed of the threats, and the size of the engagement.

Measures of Performance are quantities that describe system properties or mission requirements. MOPs for a command and control system may include reliability, survivability, cost, and probability of kill. The mission requirements should be expressed by the same quantities as the system MOPs, e.g., minimum reliability or survivability, maximum cost, or minimum probability of kill. System parameters are defined within the system boundary; MOPs may be defined within the boundary, or they may include aspects of the environment.

Measures of Effectiveness (MOEs) are quantities that result from the comparison of the system MOPs to the mission requirements. They reflect the extent to which the system meets the requirements. To evaluate the MOEs, it is necessary to go outside the boundary and consider the environment. Only then could the effect of the system on the mission outcome be evaluated.

In this methodology for assessing effectiveness, the system MOPs and the mission requirements must be modeled and analyzed independently, but in a common context. The system capabilities should be determined independently of the mission requirements, and the mission requirements should be derived without considering the system to be assessed. Developing requirements with a specific system implementation in mind leads to obvious problems regarding the credibility of the assessment.

The analytical formulation of the methodology for system effectiveness analysis (SEA) and its relationship to the Modular Command and Control Evaluation Structure (MCES) are described in Section 2, while a recent application to a problem is described briefly in Section 3. Finally, in Section 4 some general consideration on measures of effectiveness are presented.

2. THE TWO APPROACHES: MCES AND SEA

The Modular Command and Control Evaluation Structure (MCES) is shown in Figure 2. It consists of seven modules organized in a sequential manner. In reality, an analyst employing MCES would iterate between the modules, as appropriate, until a satisfactory solution to the problem was obtained.

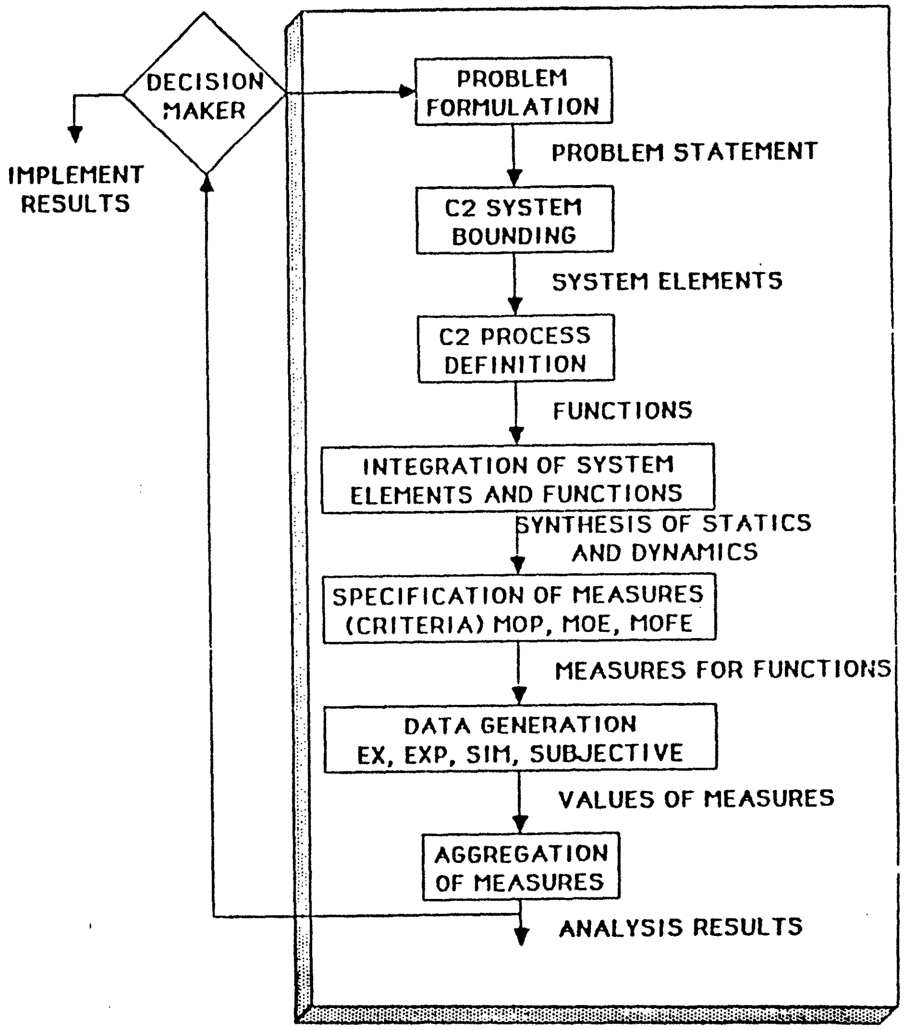

Figure 2. Modular Command and Control Evaluation Structure (MCES)

In the first module, the decisionmaker's requirements are expressed in the form of a problem statement consisting of a set of objectives and the associated assumptions. In the second module, the problem statement is used to bound the problem, i.e., specify the boundaries of the system to be analyzed. This is the most critical part of the MCES methodology and the one that often requires a number of iterations. The result is the identification of the system components and their interconnections. In the third module, the particular command and control process is described. The result is the specification of the set of functions such as "sense", "assess", "generate", "select", and "direct" [8]. The allocation of the functions derived in module 3 to the components and structure is carried out in module 4. Thus, in the first four steps, the complete formulation of the problem is achieved.

The next three modules constitute the "solution" to the problem. In module 5, the various measures that are relevant for the problem in question are specified: MOPs, MOEs and, if appropriate, Measures of Force Effectiveness or MOFEs. Such measures as survivability, reliability, and interoperability are typical examples of MOPs. However, these measures represent general concepts; there is need for problem-specific variables that are measurable and can represent these MOPs, i.e., instantiations for the specific C^3 system being evaluated. The values of these variables should be computable from data generated by the system. Finally, in module 7, the aggregation of MOEs is carried out.

The MCES methodology, as described briefly above, provides a logical and orderly structure that guides the analyst through the process of formulating the measures of effectiveness that are appropriate for the problem in question. The System Effectiveness Analysis, (SEA) however, focuses on the quantitative aspects of obtaining and evaluating measures of effectiveness. Indeed, the steps of the SEA can be embedded in MCES and especially in the last three modules.

The first step in (SEA) consists of defining the System, the Environment, and the Context, followed by the selection of the parameters that influence the system MOPs. By definition, these parameters are considered mutually independent, since they constitute the "independent variables" in the analytical formulation of the methodology. This step is a specifc implementation of Modules 1 to 4 in MCES.

In the second step, the analogous procedure is carried out for the mission. Parameters of the mission are defined that are consistent with the environment and the context. This step does not have a direct correspondence to the modules of MCES, but is implicit in the feedback loop between the aggregation modules and the decisionmaker (Fig. 2).

The third step consists of defining MOPs for the system that characterize the properties that are of interest in the analysis. The MOPs are expressed as functions of the parameters. The values of the MOPs could be obtained from the evaluation of a function, from a model, from a computer simulation, from a test bed, or from empirical data. Each MOP depends, in general, on a subset of the parameters, i.e.,

$$MOP_i = f_i(x_i, \ldots, x_k). \tag{1}$$

MOPs may or may not be independent from each other; two measures are interdependent, if they have parameters in common. A system realization results in the set of parameters taking specific values $\{x_i\}$. Substitution of these values in the relationships (1) yields values for the set {MOP}. Thus, any specific realization can be depicted by a point in the MOP space.

The fourth step consists of selecting the models that map the mission parameters y_i into the requirements:

$$R_m = f_m(y_1, \ldots, y_n). \tag{2}$$

Some of the mission requirements may be interrelated through dependence on common parameters. It is also possible to introduce directly some constraints between the requirements, e.g., a trade-off relationship between delay and accuracy. However, it is preferable that such trade-off relationships be derived through the functions or models that define MOPs or requirements in terms of the mission parameters. Specification of values for the mission parameters results in a point or region in the mission requirements space.

The two spaces, the system MOP space and the mission requirements space, although of the same dimension, may be defined in terms of different quantities, or quantities scaled differently. Therefore, the fifth step consists of transforming the system measures and mission requirements into a set of commensurate attributes defined on a common attribute space. For example, one of the system MOPs may be vulnerability, while the corresponding mission requirement may be survivability. Since they both reflect the same concept - the effect of external actions - one of them may be chosen as the common attribute, say, survivability, while the other one will then be mapped into the first one.

The Measures of Performance for the system are functions of the system parameters. Consequently, as the x's in Eq. (1) vary over their allowable ranges, the MOPs take values that generate a locus in the MOP space. This transformation is shown in Figure 3. The resulting locus is called the System Locus, L_s.

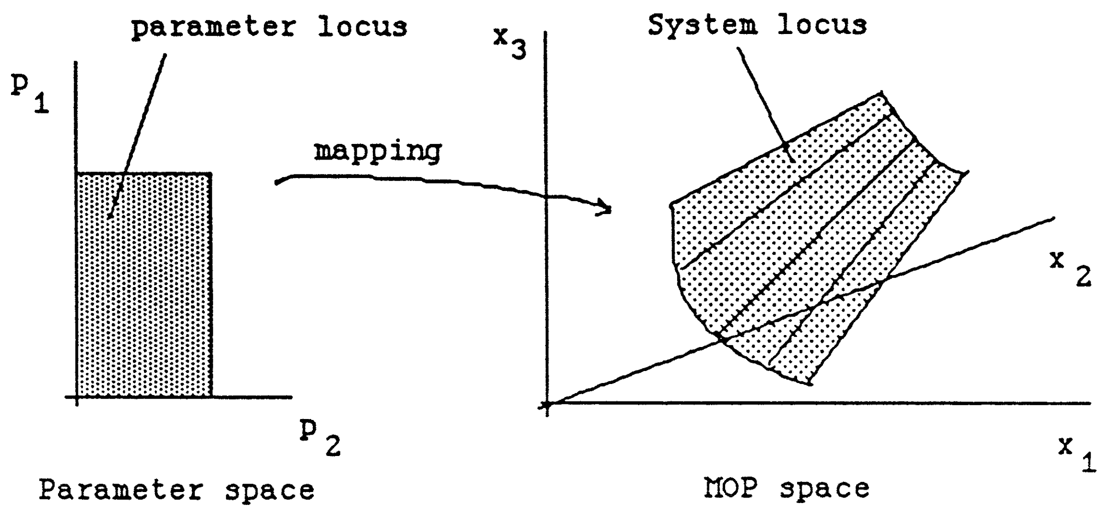

Figure 3. System Locus

Analogously, the set of values that satisfy the mission requirements, Eq. (2), constitute the Mission Locus, L_m (Fig. 4). The two loci are constructed in step 6, after the common MOP space has been defined in step 5.

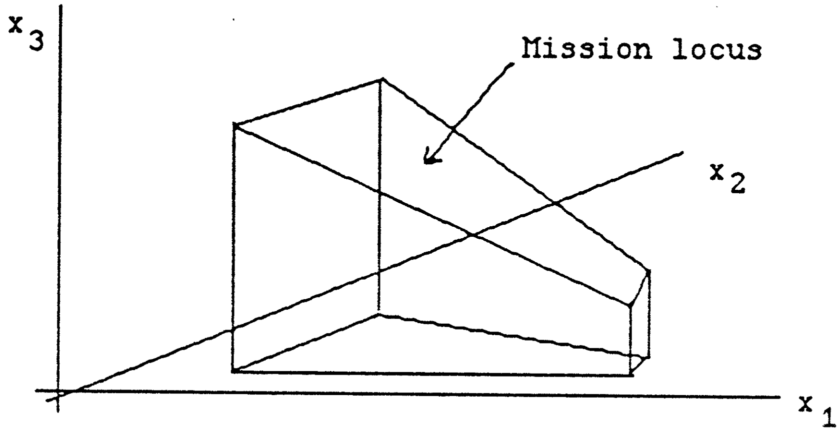

Figure 4. Mission Locus

The seventh step is the key one in analyzing the effectiveness of a C^3 system in view of the mission that is to be carried out. It consists of procedures for comparing the system's MOPs and mission's requirements through the geometric properties of two loci. The geometric relationship between the two loci can take one of three forms:

(1) The two loci do not have any points in common, i.e., the intersection of L_s and L_m is null:

$$L_s \cap L_m = \phi. \tag{3}$$

In this case, the system does not satisfy the mission's requirements, and one would define the effectiveness to be zero, regardless of which specific measure is used.

(2) The two loci have points in common, but neither locus is included in the other:

$$L_s \cap L_m \neq \phi. \tag{4}$$

and

$$L_s \cap L_m < L_s \text{ and } L_m. \tag{5}$$

In this case, a subset of the values that the MOPs may take satisfies the mission requirements. Many different measures can be used to described the extent to which the system meets the requirements. Each of these measures may be considered an MOE. For example, let V be such a measure. Then an effectiveness measure can be defined by

$$E_1 = V(L_s \cap L_m)/V(L_s) \tag{6}$$

which emphasizes how well the system capabilities are used in the mission, while

$$E_2 = V(L_s \cap L_m)/V(L_m) \tag{7}$$

expresses the degree of coverage of the requirements by the system capabilities.

(3) The mission locus is included in the system locus:

$$L_s \cap L_m = L_m. \tag{8}$$

In this case, it follows from (8) that L_s is larger then L_m and, consequently, the ratio defined by (6) will be less than unity. This result can be interpreted in two ways. First, only certain system attribute values meet the requirements of the mission. The second interpretation is that the use of this system for the given mission represents an inefficient use of resources since the system capabilities exceed the mission requirements. Inefficiency, in turn, implies lower effectiveness.

The measures of effectiveness given by (6) or (8) are partial measures. Let these partial measures be denoted by $\{E_r\}$. To combine these into a single global measure, utility theory may be used. Therefore, the subjective judgements of the system designers and the users can be incorporatred directly into the methodology in two ways: (1) by choosing different partial measures, and (2) by selecting a utility function. The global effectiveness measure is obtained, finally, from

$$E = u(E_1, E_2, \ldots, E_k). \tag{9}$$

This is the last step of the SEA methodology and corresponds to the seventh module of the MCES.

3. EFFECTIVENESS OF AN AIR DEFENSE SYSTEM*

In the 1970's, the problem of aircraft identification in the NATO environment was investigated and the implication of indirect or third party ID was explored. Indeed, because of the speed of the threats and the short reaction time available, indirect ID for distinguishing friends, foes, and neutrals (IFFN) becomes crucial.

To assess the effectiveness of the indirect ID process, a test bed was developed in order "to assess baseline capabilities within the air defense C^2 structure to perform the IFFN function, to identify deficiencies in the performance of that function, and to define potential near-term procedural and equipment modifications for further testing". This test bed [9] is a surrogate for the actual system which, of course, can hardly be tested. By conducting experiments on the IFFN Joint Test and Evaluation facilities, it is expected that the effectiveness of the actual system can be assessed.

*This section is based on the recent thesis by Philippe J. F. Martin [6].

The IFFN System considered is shown in Figure 5; it is composed of nodes corresponding to Fire Direction Centers (FDC), Control Reporting Centers (CRC), Special Information System (SIS) and the weapons systems (Patriot, Hawk, F-15, F-16).

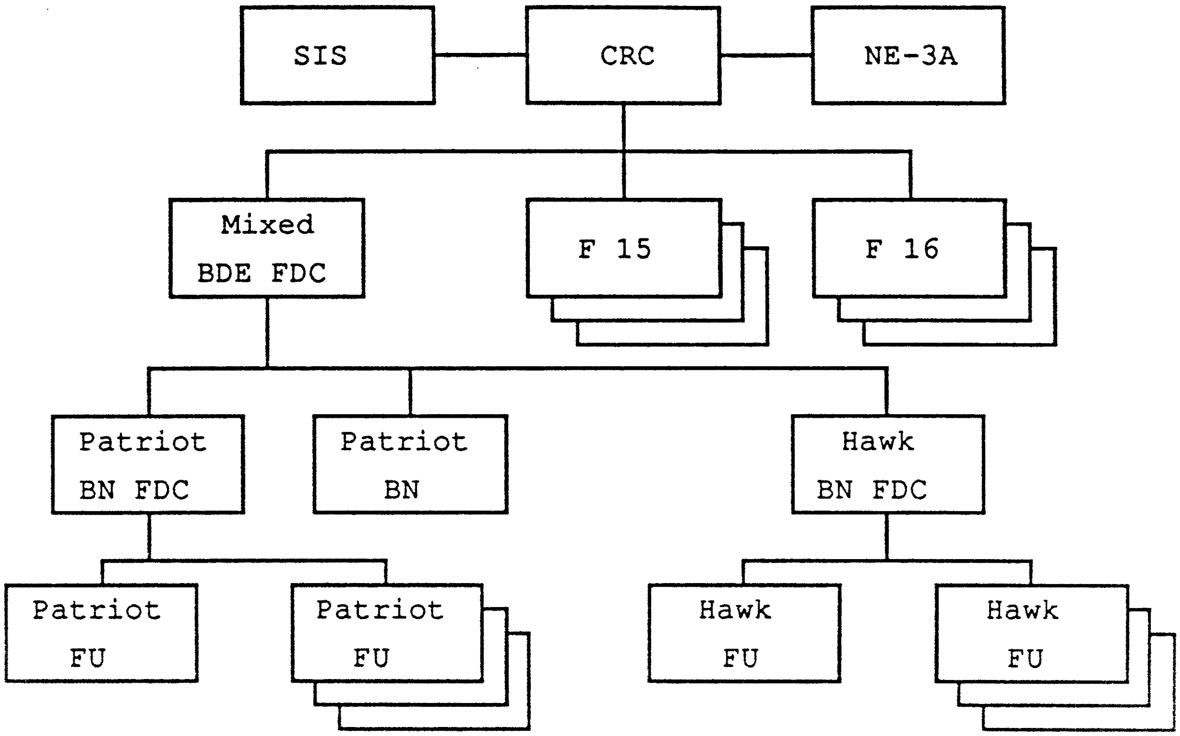

Figure 5. Structure of the Actual IFFN System

The mission of the system is to engage and destroy hostile airborne targets and, therefore, deny the enemy access to the defended airspace and to prevent attacks on friendly assets. At the same time, the system must prevent attacks on friendly or neutral aircraft. To accomplish this mission, the air defense system must perform a number of functions: detection, tracking, identification, allocation, engagement, and target kill.

As a first order approximation to the actual problem, a simplified model was introduced [6] for which five system parameters were defined:

(1) time needed to transmit information from one node to another (it depends on whether the SIS is included or not);

(2) range from aircraft to the Fire Support Coordination Line (FSCL) at the time of detection; it depends on the variable Air Control Procedure.

(3) quality of identification;

(4) level of centralization of control; and

(5) quality of target allocation and engagement. This is dependent on the quality of the Q and A IFF devices.

The MOPs for assessing the system should have clear physical meaning -- that helps in defining variables for measuring them -- and reflect the tasks to be performed. Three MOPs have been defined.

The first MOP reflects the success of the air defense task; it is measured by the normalized ratios of the remaining friendly forces to the remaining enemy forces. The second MOP measures the number of neutrals shot down by the air-defense system. The last MOP is the distance from the FSCL that the enemy has achieved when the air battle ends.

When the five parameters are allowed to vary over their admissible ranges, i.e.,

$$p_{i,min} \leq p_i \leq p_{i,max} \qquad i = 1,\ldots,5$$

then the complete system locus is obtained. The plots of the locus have been generated by a special purpose graphics package [5] for an IBM PC/AT and an HP 7475 plotter. In Figures 6 and 7, the two dimensional projections of the locus L_s are shown.

The mission requirements have been assumed to be the following: that the friendly forces "win" the battle, that a small percentage of neutrals is engaged, and that the enemy forces have not been allowed to come within range of friendly assets on the ground. These conditions define a

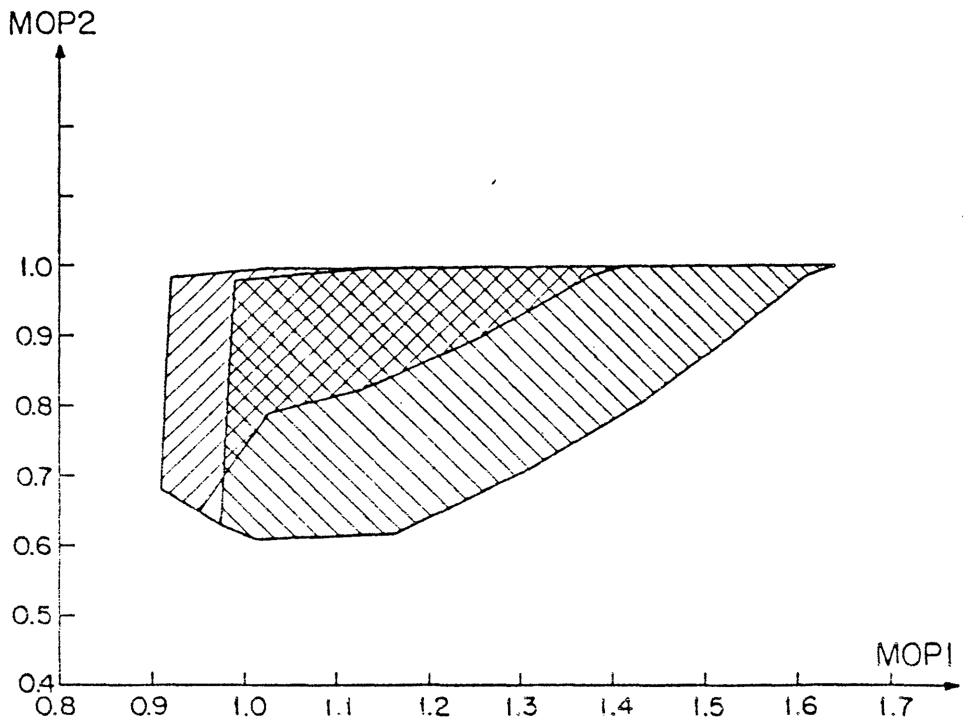

Figure 6. Entire System Locus Projected on the Plane MOP1/MOP2

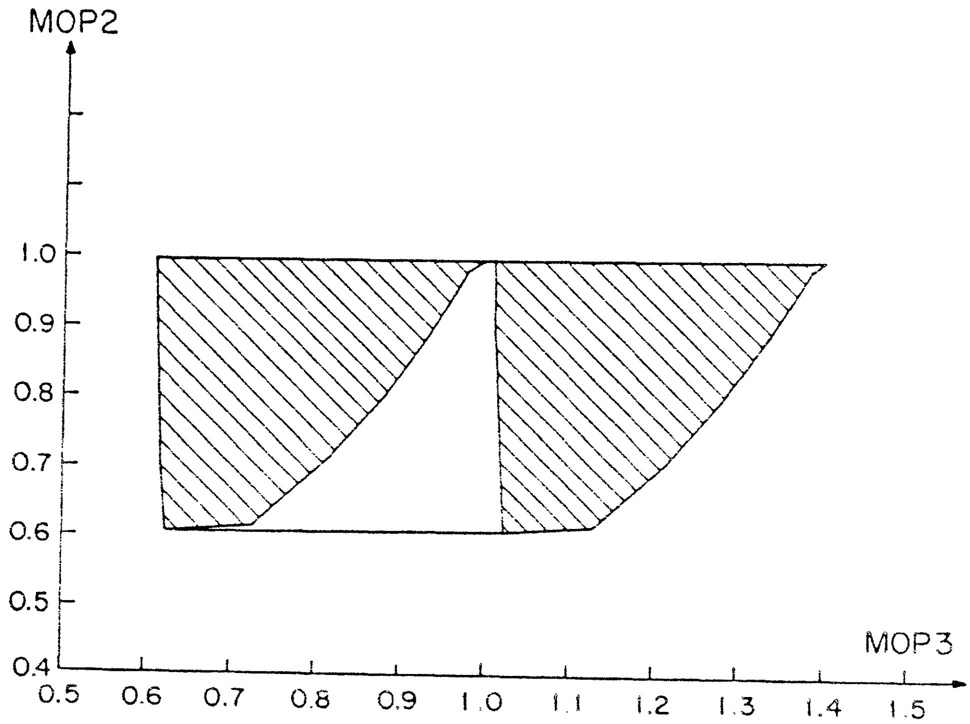

Figure 7. Entire System Locus Projected on the Plane MOP3/MOP2

rectangular parallilepiped in the MOP space (Figure 8).

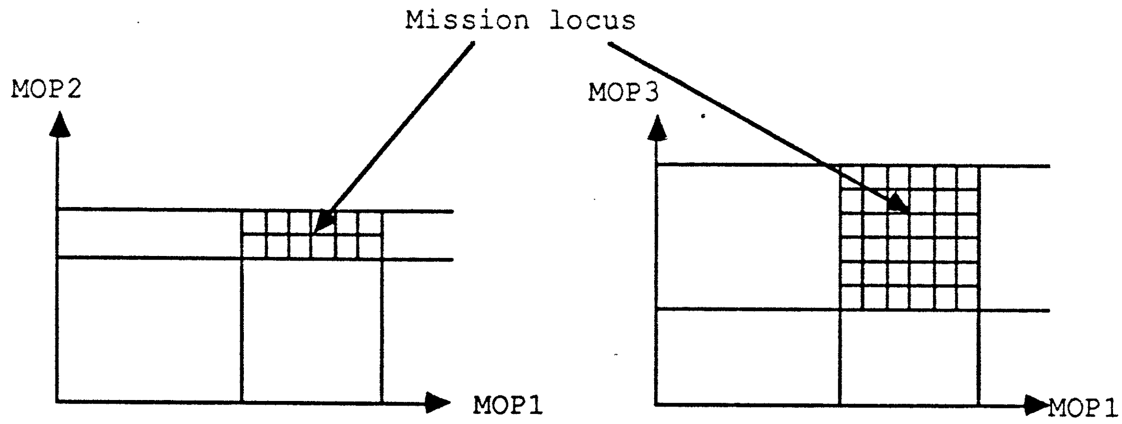

Figure 8. Projections of the Mission Locus

The appropriate measure of effectiveness is the one given by Eq. (6). For the hypothetical values used in this example, E_1 was calculated to be approximately 0.3. The actual value is not significant; what is significant is that the methodology makes it possible to compute changes in the value when functions or nodes are eliminated from (or added to) the system [6].

4. CONCLUSION

In the previous three sections, a quantitative methodology for assessing C^3 systems was described and an illustrative example outlined. The methodology was imbedded in the MCES which provides a framework for formulating C^3 system evaluation problems. The use of the IFFN test bed as the illustrative example raises, however, a new class of C^3 issues that are relevant for large scale systems that are not easily tested in the field under realistic operational conditions. The most prominent of these issues is one of <u>credibility</u>: how credible are the results obtained from models, simulations, and test beds with respect to the actual system's performance.

A usual approach to the problem is to increase the fidelity of the components in the expectation that the test bed will be a "credible" surrogate for the real system. However, increased fidelity leads to increased complexity and, hence, reduction in the transparency of the results.

In considering the role of models and test beds in the assessment of C^3 systems, three functional groups can be identified: (a) the modeler, or test bed builder, who conceives, designs, and implements the test bed; (b) the user who is concerned with obtaining quantitative and qualitative information; and (c) the decisionmaker, who requires pertinent, timely analyses and recommendations from his staff.

If the identification of the three functional groups is accepted, then the issues of validity, verification, and credibility can be put in perspective.

Verification is a test of whether the model or test bed behaves exactly as its designer intended.

Validation is a test of whether the model or test bed behavior is in agreement with the real system it represents with respect to the specific purposes for which the model has been designed.

Verification includes testing software, testing algorithms for convergence, checking that data are entered properly and used correctly and, generally, ensuring that the implemented model is true to its conception and error free. Verification does not address the question of whether the conception is valid.

Validation is an issue between the model user and the modeler because validity is closely tied to the function the model will perform. A model may be "valid" for one set of uses and invalid for many others that appear to be very similar. While the differences may seem minor, they may violate some of the implicit assumptions in the model.

What is important in considering a "verified" model for use in assessment is whether its underlying assumptions and theories, or the approximations regarding the model's boundaries and the interactions between the subsystems, are compatible with the issue to be analyzed. Even though a model may have been verified by the modeler and considered valid by the model user for a specific study, there is still a third issue: credibility of the model with decision makers [10]. G. L. Johnson has stated that "problem solving analyses are credible with decision makers, if they pass four tests: (1) coherence, (2) correspondence, (3) clarity, (4) workability " [11]. The first two, coherence and correspondence, can be interpreted as tests for validation and verification, while the clarity test is one of understandability. "When the decision maker applies the test of workability, he checks the proposed solution and projected consequence of the solution to see if he thinks the outcomes would actually result from the prescribed action and, if they result, whether they will solve the problem before him" [11]. A fifth test can be added for evolving systems, that of repeatability, which measures the consistency over time with which a model generates understandable and workable results.

This concept of credibility, with its attendant objective and subjective tests, forms interactive links between the three entities - the modeler, the user, and the decisionmaker.

In view of the expected increase in the use of test beds and demonstrations, credibility may well become a dominant measure of effectiveness in the future. Unfortunately, there are hardly any procedures or tools for assessing credibility. Both conceptual and analytical work is needed to address this issue.

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